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van Dieen, J.H.; van der Veen, A.; van Royen, B.J.; Kingma, I.

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Fatigue Failure in Shear Loading of Porcine Lumbar Spine Segments

Jaap H. van Dieën, PhD,*† Albert van der Veen, MSc,*‡ Barend J. van Royen, MD, PhD,*§ and Idsart Kingma, PhD*†

Study Design. An *in vitro* study on porcine spinal segments.

Objectives. To determine the differences in mechanical behavior and fatigue strength in shear loading between intact spinal segments and segments without posterior elements, and between segments in neutral and flexed positions.

Summary of Background Data. Limited data are available on shear strength of spinal segments. Literature suggests that shear loading can lead to failure of the posterior elements and failure of the disc, when the posterior elements cannot provide adequate protection.

Methods. In 2 experiments, 18 and 20 spines of pigs (80 kg) were used, respectively. Shear strength of the T13–L1 segment was tested, while loaded with 1600-N compression. L2–L3 and L4–L5 segments were loaded with a sinusoidal shear between 20% and 80% of the strength of the corresponding T13–L1 segment and 1600-N compression. In experiment No. 1, the posterior elements were removed in half the segments. In experiment No. 2, half the segments were tested in the neutral position, and half were tested in 10° flexion.

Results. The group without posterior elements had failure earlier than the intact group. In the group without posterior element, stiffness increased on failure; in the intact group, it decreased. In experiment No. 2, no differences between groups were found.

Conclusions. Repetitive shear loading can induce failure of porcine spinal segments, likely caused by fracture of the posterior elements, and, although repetitive anterior shear forces can also induce disc damage, this appears not to occur in intact segments, not even when flexed close to maximal.

Key words: spondylolisthesis, spondylolysis, intervertebral disc, shear injury, fatigue failure. **Spine 2006;31:E494–E498**

In physically exerting tasks such as lifting, the lumbar spine is subjected to torques caused by trunk bending and twisting, and to high forces that result mainly from muscle contractions. High and repetitive torques can lead to injury of ligaments and the intervertebral disc, especially when twisting and bending are combined.[1–5] The forces acting on the spine can be decomposed into compression, anteroposterior shear, and lateral shear components. Compression forces have been relatively well studied, both with respect to the magnitude that these forces reach during physically exerting tasks, as with respect to their potential to cause injury. A review of these data has led to the conclusion that compression forces may well be a cause of low back injury and subsequent low back pain.[6]

Much less is known about anteroposterior and lateral shear forces. However, several studies have indicated that substantial anterior directed shear forces occur, especially at the L5–S1 level. Anterior shear forces at L5–S1 have been estimated to reach peak values of up to 2000 N.[7–10] *In vitro* experiments have shown that anterior shear loading of human spinal segments can cause bony failure at forces between 600 and 3000 N.[11,12] Comparing these values to the magnitude of shear forces estimated to occur during lifting suggests a potential injury mechanism. In line with this result, an epidemiologic study found peak shear loading to be associated with low back pain report.[13]

However, *in vitro* experiments have shown that the injury from anterior shear loading most often is a fracture of the posterior elements of the spine, with the pars interarticularis being most frequently affected.[11,12,14] This type of failure can be expected to show up on radiograph examination in most cases. Indeed, spondylolytic spondylolisthesis (*i.e.*, a forward displacement of a vertebra [usually L5] relative to the vertebra below subsequent to a fracture of the posterior elements) is a fairly common finding,[15] with a prevalence of around 5% to 6% in adult males and up to 11% in specific groups, such as female gymnasts.[16] Yet, it is by no means a typical finding in patients with low back pain. Moreover, the presence of spondylolysis and spondylolisthesis is not consistently associated with low back pain, and several sources have reported such findings in asymptomatic subjects.[17]

Degenerative spondylolisthesis is a forward displacement of a vertebra relative to the vertebra below it, without a fracture of the posterior elements but with degeneration of the intervertebral disc. It is a prevalent disorder most often found at the L4–L5 level.[18] The occurrence of degenerative spondylolisthesis strongly suggests that the intervertebral disc provides part of the resistance against forward shear displacement. Indeed,

From the *Institute for Fundamental and Clinical Human Movement Sciences; †Faculty of Human Movement Sciences, "Vrije Universiteit Amsterdam"; and Departments of ‡Medical Physics and Technology, and §Orthopedic Surgery, VU University Medical Center, Amsterdam, The Netherlands.
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Address correspondence and reprint requests to Jaap H. van Dieën, PhD, Faculty of Human Movement Sciences, Vrije Universiteit Amsterdam, VanderBoechorststraat 9, NL-1081 BT Amsterdam, The Netherlands; E-mail: J.vanDieen@fbw.vu.nl

the intervertebral disc has a high shear stiffness[19] and has been estimated to contribute 70% of the shear stiffness of porcine cervical spinal segments.[14] This suggests that the intervertebral disc may be at risk for injury during shear loading. However, as described previously, overloading a spinal segment in shear in a single cycle has led predominantly to fractures of the posterior elements. It is questionable, though, which structure would be first to fail in repetitive shear loading below the failure threshold of the neural arch. Cyron and Hutton[20] tested spinal segments in repetitive shear loading after removal of the posterior elements. Substantial creep deformation resulted, but data on failure were not reported.

The aim of the present study was to add data on the sparsely investigated topic of shear strength of the spine. Specifically, we addressed fatigue strength, which, to our knowledge, had not been studied previously. We compared mechanical behavior and fatigue strength in shear loading between porcine spinal segments with and without posterior elements. We hypothesized that the posterior elements would contribute to shear stiffness and, as such, provide protection against shear injury leading to earlier injury in segments without posterior elements. Next, we compared mechanical behavior and fatigue strength between segments in neutral and 10° flexed positions. We hypothesized that in the flexed segments, the intervertebral disc would be loaded more because of reduced facet contact and increased prestrain of the posterior anulus fibrosus, leading to earlier failure.

Methods

Specimens and Specimen Preparation. For experiment No. 1, the lumbar spines (T13–L5 segments) of 18 immature domestic pigs (mean weight 81.9 kg, standard deviation 2.3) were obtained from the slaughterhouse. For experiment No. 2, the lumbar spines of 20 immature pigs (mean weight 75.9 kg, standard deviation 6.2 kg) were obtained. The segments were cleared from excess muscle tissue, while all ligamentous tissue was left intact. Specimens were stored frozen at −20°C. Before testing, the segments were left to thaw for 14–24 hours at 4°C. Subsequently, they were sectioned to obtain 3 segments: T13–L1, L2–L3, and L4–L5. These 3 segments were tested in a single session, and while 1 segment was tested, the other segments were stored at 4°C. Both vertebrae were embedded in cups with bismuth, keeping all articulating parts free. For extra fixation, wood screws were screwed into the vertebral body to a maximum depth of 0.5 cm. During preparation and testing, the specimens were kept moist by spraying with saline. During testing, the articulating part of the segment was kept wrapped in cling film. In larger specimens, transverse and spinous processes were partly removed to allow embedding in the cups used. For experiment No. 1, in half the specimens, all posterior elements were removed by sectioning through the pedicles.

Procedure. In both experiments, the T13–L1 segment of each specimen was used to estimate the shear strength of the specimen, so that remaining segments could be tested at a percentage of this value. An anterior shear force was applied on the cranial vertebra using a hydraulic materials testing machine (model 8872; Instron & IST, Canada). The caudal vertebra was fixed on a plateau that could translate in the axial direction with negligible friction but did not allow movement in the shear direction. The only structures resisting shear displacement of the cranial vertebra were the articulations with the caudal vertebra. Using a dead weight connected through a pulley system to the plateau, segments were loaded with a compression force of 1600 N. Shear strength was determined at a strain rate of 0.1 mm/s. Force and displacement were recorded and digitized at 100 Hz (Instron Fast Track 2). The test was stopped after hearing a clear crack or after a displacement of 1 cm. The ultimate shear force was determined from the load-displacement curve.

Subsequently, L2–L3 and L4–L5 segments were tested using the same setup and same compressive load. From each specimen, L2–L3 was allocated to 1 experimental group and L4–L5 to the other group. By using an even number of specimens and counterbalancing group allocation, we made sure that both groups contained equal numbers of both types of segments. In experiment No. 1, 2 groups were tested, including 1 with posterior elements intact and 1 without posterior elements, leaving the intervertebral disc as the only structure providing shear resistance. All these specimens were tested in a neutral position. In experiment No. 2, half the (intact) segments were tested in the neutral position and half were tested in a 10° flexed position. Placing a wedge under the cup in which the cranial vertebrae were embedded imposed flexion. All L2–L3 and L4–L5 segments were loaded with a sinusoidal varying shear force (0.5 Hz) between 20% and 80% of the strength of the corresponding T13–L1 segment. Shear displacement and force were continuously recorded at 10 Hz. Tests were stopped after 1500 loading cycles.

Analysis. For each loading cycle, the average displacement and amplitude of displacement were determined, and these data were plotted to determine the instant of failure (Figure 1). A single observer who was blinded to the experimental condition determined failure as the first obvious discontinuity in average displacement as well as amplitude of displacement within the cycles (Figure 1C). Trials were presented to the observer for determination of failure in random order. The median amplitude of the displacement over the 5th to 10th cycle was determined as an indicator of initial shear stiffness of the segments. Furthermore, the median amplitudes of the displacement more than 5 cycles just preceding failure and the 5th to 10th cycle after failure were compared to indicate changes in stiffness. L4–L5 and L2–L3 segments from the same specimen were treated as dependent observations, and all statistical tests were performed using Wilcoxon matched pairs tests.

Results

Experiment No. 1

Shear strength of the T13–L1 segments ranged from 1062 to 1985 N. Table 1 provides an overview of all data and test results. As hypothesized, removal of the posterior elements led to a decrease in shear stiffness, evidenced by a significantly larger displacement during the initial cycles in the group without posterior elements.

In the group with posterior elements, 6 segments did not fail within the 1500 cycles applied. In the group without posterior elements, 3 segments did not fail. All subsequent analyses concern only those segments that

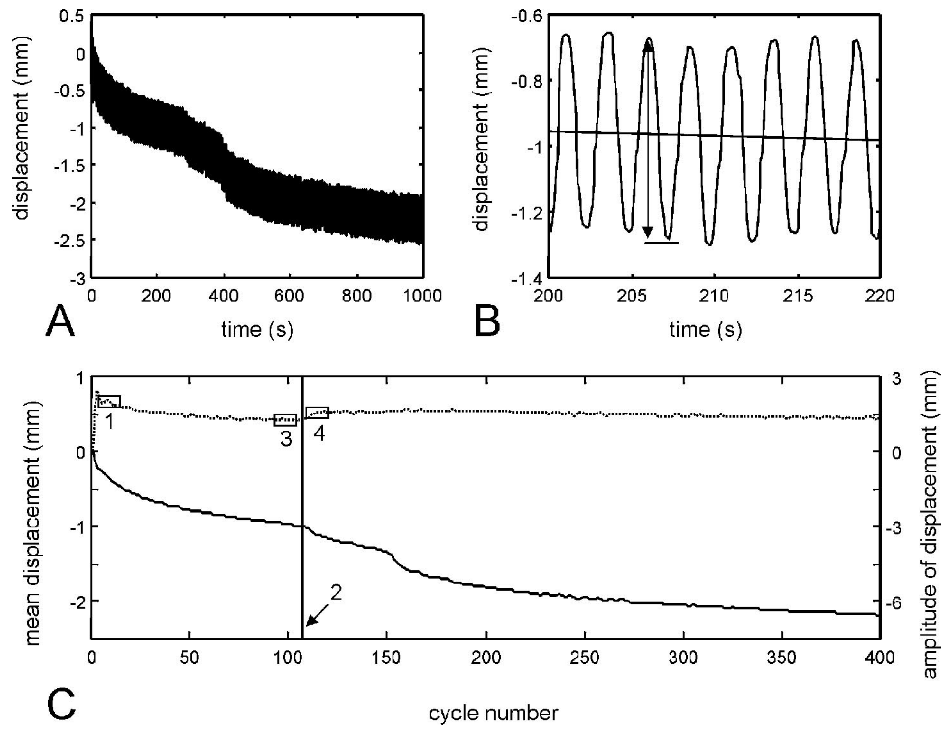

Figure 1. **A**, An example of the shear displacement as a function of time. **B**, Magnification of a part of the time series, with the mean displacement per cycle and an arrow indicating the definition of the displacement amplitude. **C**, The mean displacement and amplitude as a function of cycle number, illustrating the dependent variables: (1) initial displacement amplitude, (2) time to failure, (3) displacement amplitude before failure, and (4) after failure.

failed within the 1500 cycles, or, for comparisons between groups, from spines in which both the L2–L3 and L4–L5 segments failed within the 1500 cycles. Time to failure of the specimens that did fail was significantly longer in the group with posterior elements. In the group with posterior elements, the amplitude of the displacement over the cycles just after failure was significantly larger than the amplitude preceding failure, indicating a loss of stiffness. In contrast, in the group without posterior elements, displacement within cycles significantly decreased after failure, indicating increased stiffness. After failure, the shear amplitude was no longer different between groups.

Experiment No. 2

Shear strength of the T13–L1 segments ranged from 805 to 2416 N. Because the intervertebral disc may be less protected by the posterior elements when the specimen is flexed, experiment No. 2 compared specimens tested in flexed and neutral positions. Initial displacement did not differ between the groups tested in these positions (Table 2).

In the neutral position, 3 segments were not damaged within the 1500 cycles applied. In the flexed condition, 4 segments remained intact. The remaining analyses were performed only on those segments that failed within the 1500 cycles, or, for comparisons between groups, from spines in which both the L2–L3 and L4–L5 segments failed within the 1500 cycles. None of these analyses revealed significant differences between the flexed and neutrally positioned segments. Thus, in contrast to our hypothesis, shear failure did not occur earlier in flexed positions. All results were consistent with those in the segments tested intact in experiment No. 1.

■ Discussion

In all groups of segments tested with posterior elements, the stiffness decreased after failure. In line with the literature on single-cycle shear loading,[11,12,14] this suggests that repetitive shear loading can lead to bony failure of the posterior elements. Bony failure was confirmed on nonsystematic observations of the tested segments. After this failure, it appears that the posterior elements were

Table 1. Median Values and Ranges of All Dependent Variables and *P* Values (Wilcoxon matched pairs) for Differences Between Groups With and Without Posterior Elements, and for Shear Amplitudes Before and After Failure

	With Posterior Elements	Without Posterior Elements	*P*
Initial shear amplitude	1.14 mm (range 0.66–1.48)	1.50 mm (range 1.06–1.98)	0.013 (n = 18)
Time to failure	1096 seconds (range 66–1636)	144 seconds (range 24–1154)	0.017 (n = 11)
Shear amplitude before failure	1.05 mm (range 0.72–1.34)	1.39 mm (range 1.05–1.97)	0.003 (n = 11)
Shear amplitude after failure	1.10 mm (range 0.79–1.62)	1.15 mm (range 0.51–1.84)	1.00 (n = 11)
Amplitude before minus amplitude after failure	−0.10 mm (−0.51 to −0.03)	0.24 mm (−0.23 to 1.14)	0.013 (n = 11)
P value for difference before and after failure	0.002 (n = 12)	0.004 (n = 15)	

Table 2. Median Values and Ranges of All Dependent Variables and *P* Values (Wilcoxon matched pairs) for Differences Between Groups Tested in Neutral and Flexed Positions, and for Shear Amplitudes Before and After Failure

	Neutral	Flexed	*P*
Initial shear amplitude	1.26 mm (range 0.58–1.86)	1.27 mm (range 0.41–1.86)	0.173 (n = 20)
Time to failure	276 seconds (range 2–2762)	246 seconds (range 12–2762)	0.225 (n = 16)
Shear amplitude before failure	1.26 mm (range 0.46–1.79)	1.27 mm (range 0.41–1.86)	0.500 (n = 15)
Shear amplitude after failure	1.47 mm (range 0.45–2.35)	1.26 mm (range 0.39–1.79)	0.893 (n = 15)
Difference in amplitude before and after failure	−0.08 mm (−1.15 to 0.91)	−0.08 mm (−0.32 to 0.12)	0.686 (n = 15)
P value for difference before and after failure	0.015 (n = 17)	0.026 (n = 16)	

no longer contributing much to shear stiffness because the shear amplitude no longer differed from that in the group without posterior elements.

When posterior elements had been removed, injury occurred more frequently within the number of cycles applied. These injuries presumably affected the intervertebral disc because this was the only articulating structure between the 2 vertebral bodies. This finding suggests that the intervertebral disc in the neutral position is protected from shear damage by posterior elements stiffness. When this protection is lacking, the probability of injury caused by shear is relatively high because in the group without posterior elements, injuries occurred in more specimens and already after fewer cycles than in the intact group. The increase in stiffness after failure, evidenced by smaller amplitudes after failure, is most likely caused by the nonlinear stiffness of the intervertebral disc to shear displacement. After failure, a forward movement of the upper vertebra occurred (Figure 1), which would increase the strain in the anulus fibers and render them stiffer.

A lack of protection by the posterior elements against shear injury to the intervertebral disc was also expected to occur with the spine flexed close to maximally. However, our data do not support this hypothesis. The 10° flexion applied, which was close to maximum flexion for the segments tested, did not affect the time to failure or the mechanical behavior before and after injury. It appears that facet joint contact is still sufficient to contribute to shear stiffness and protect the intervertebral disc from injury, in line with model predictions made by Cholewicki *et al*.[21]

The early failure of the specimens tested without posterior elements indicates that the posterior elements provide an important protection against shear injury. In this light, the occurrence of iatrogenic spondylolisthesis after laminectomy can be understood. Laminectomy can be expected to cause a loss of stiffness and strength of the pars interarticularis, depending on the amount of bone mass removed in the procedure. Loss of stiffness of this structure would lead to increased loading of the intervertebral disc in shear and potentially intervertebral disc injury or anterolisthesis caused by creep deformation. The loss of strength would predispose to fractures of the pars interarticularis and subsequent anterolisthesis.

It has been shown that shear stiffness of spinal motion segments increases with compressive loading.[22,23] Therefore, we applied a 1600-N compressive preload to the segments. *In vivo*, peak compression forces on the spine covary with peak shear forces across movement tasks.[10] Because high shear forces were applied (up to 80% of the estimated maximum), a substantial level of compression (2 times body weight) was used. It could be argued that, *in vivo*, even higher compression forces would coincide with near-maximum shear forces. However, because of the nonlinear effect of compression on shear stiffness,[22,23] a further increase in compression force would probably not have affected the results. In addition, over the course of a movement, covariation of compression and shear can be expected to occur, whereas for practical reasons, a constant compression force was applied in our study. We do not expect this to have had a large effect on the results of this study.

To fit the segments into the cups for fixation, small part of the spinous and transverse processes had to be removed. Attachments of the supraspinous and intertransverse ligaments were likely affected in this procedure. We expect this to have a negligible effect on shear strength and, therefore, on the current results. With anterior shear, the spinous processes approach each other, and, consequently, the supraspinous ligaments cannot provide resistance to shear, as was confirmed by serial sectioning in a study by Yingling and McGill.[14] The removal of part of the intertransverse ligaments may have had some effect, but because of their longitudinal orientation and limited cross-section, this effect could only have been minor.

We chose to perform this experiment using porcine spinal segments for their easy availability. The main difference with human lumbar segments is the smaller size, while compressive and shear strength are comparable. Although caution with interpretation of the results in a quantitative sense is warranted, in our view, these segments provide a satisfactory model for the mechanics of the human lumbar spine in qualitative studies, such as the present one. McLain *et al*[24] noted a good comparability of the morphology of porcine and human lumber vertebrae. Similarly, for practical reasons, we have chosen to use frozen segments. Although it has been argued in one study that this could influence the mechanics of the intervertebral disc,[25] another more recent study from the same group revealed no major effects of careful frozen storage over a time comparable to the one used in the present study.[26]

Further caution against the quantitative use of the data presented here should be given. Failure of the par interarticularis caused by shear is likely the consequence of the bending moments imposed on this structure. *In vivo*, forces of locally inserting muscles may likely reduce these bending moments. This effect is not considered in current models of the spine and lumbar musculature. In conclusion, repetitive shear forces can induce failure of porcine spinal segments, likely caused by fracture of the posterior elements, and, although repetitive anterior shear forces can also induce intervertebral disc damage in the porcine spine, this appears not to occur when posterior elements are present, not even when the segment is flexed close to maximal flexion.

Key Points

- We studied *in vitro* mechanical behavior of porcine spinal segments in repetitive shear loading.
- Shear stiffness was higher in intact than in segments without posterior elements.
- Shear fatigue strength was higher in intact segments.
- Shear stiffness and fatigue strength in intact segments were not affected by flexion.

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